Development of a Dilution Refrigerator for Low-Temperature Microgravity Experiments

Pat R. Roach

NASA Ames Research Center
Moffett Field, CA 94035

and **Ben P. M. Helvensteijn**

Sterling Software
Redwood Shores, CA 94065

ABSTRACT

A dilution refrigerator (DR) is the most common precooling stage for sub-millikelvin demagnetization experiments. The usefulness of the DR comes from its ability to provide cooling at 0.02-0.04 K for long periods of time while the heat of magnetization is being rejected by the demagnetization stage. In order to make these advantages of the DR available to researchers who need the microgravity of space for their experiments, we are developing a continuously-operating DR that will function in microgravity.

We have previously demonstrated that the liquid helium of the DR can be controlled by the use of capillary forces in sintered metal sponges. We have found, however, that the small pores needed to control large heights of liquid on the ground are too small to allow sufficient liquid flow for effective cooling.

We have built a shallow single-cycle version of the refrigerator that does not require large heights of liquid to be supported by capillary forces. The liquid chambers are next to each other and are filled with sinter with relatively open pores; these pores will allow much freer flow of the helium. The gravity independence of this design will be tested by tilting the system so that one chamber is slightly above or below the other and by inverting both chambers. The operation of the refrigerator should be unaffected by tilts of 5-10 degrees or by the inversion of the chambers.

A design for a continuously-operating dilution refrigerator is presented. It includes all the advantages of the single-cycle refrigerator while adding the large advantage of continuous cooling for long periods of time.

INTRODUCTION

Research at low temperatures is an extremely fruitful field because of the many phenomena that occur only there. Unusual phases of matter such as superconductors and superfluids occur at low temperatures and many subtle behaviors that are obscured by thermal motion at higher temperature can be studied in great detail at low temperatures.

Type of refrigerator needed

To carry out research at low temperatures it is necessary to have a refrigerator that 1) cools to the required temperature, 2) is reliable and, 3) if possible, operates continuously for the duration of the experiment, whether that is hours or days. On the ground the need for temperatures below 0.3 K is almost universally met by the He-3-He-4 dilution refrigerator. Its usefulness arises from the fact that it operates continuously, it can provide a substantial cooling power at temperatures from around 1.0 K down to 0.010 K and below and it can run uninterrupted for as long as several months.

There are many very interesting physics experiments that need the unique microgravity environment of space but which also need lower temperatures than are currently available. In order to investigate phenomena that occur at very low temperatures, particularly in superfluid He-3, the capability for extending research to temperatures of 0.001 K in space needs to be developed. On the ground, temperatures to 0.001 K and below are reached with adiabatic demagnetization systems that are precooled with helium dilution refrigerators. Similar temperatures can be achieved in space if the dilution refrigerator can be adapted to work in microgravity.

Microgravity Research

An important example of microgravity research is the study of liquid He-4 and He-3, both normal and superfluid phases; this has been a very productive field for many years because of the unique nature of these two very different liquids. The availability of the low gravity of space is a boon to this research because gravity has a major effect upon the behavior of the liquid. At phase transitions of the liquid, for example, the effect of gravity is to spread out the region over which the transition occurs. This can seriously mask important details of the transition. Other phenomena, such as spin-spin relaxation in He-3, are strongly influenced by the surface of a container, and the ability to form freely floating drops in microgravity would allow the influence of the container to be eliminated.

Adapting a Dilution Refrigerator for Space

The helium dilution refrigerator relies on the unique properties of liquid He-3 and He-4. Cooling to 0.010 K and below is produced when He-3 atoms cross the phase boundary that exists between liquid He-3 and liquid He-4 at low temperatures. (Essentially, He-3 ‘evaporates’ into the liquid He-4.) We have been studying the capabilities of a special dilution refrigerator;[1] this refrigerator is unusually compact and reliable, making it especially suitable for space applications. On the ground, gravity provides the force that keeps the two liquids in their required places so that the cooling can happen when and where it is needed. In space this force can be replaced with capillary forces that arise when the liquids are confined in porous sponges. We have shown[2,3] that it should be possible to develop a helium dilution refrigerator that will confine the liquids with capillary forces and still provide the cooling that makes the dilution refrigerator so valuable. This approach should work even better in microgravity.

We are sure that it is possible to adapt the dilution refrigerator to operate in microgravity. If this can be achieved, the same features that make the dilution refrigerator so attractive for laboratory research would become available to researchers in space.

PREVIOUS DEVELOPMENT

Principle of Single-Cycle Dilution Refrigerator

Figure 1 shows how such a refrigerator operates. The lowest temperatures occur in the mixing chamber where there is a phase boundary between liquid He-3 and liquid He-4. Cooling is produced when He-3 crosses this boundary into the He-4. From the mixing chamber this dilute He-3

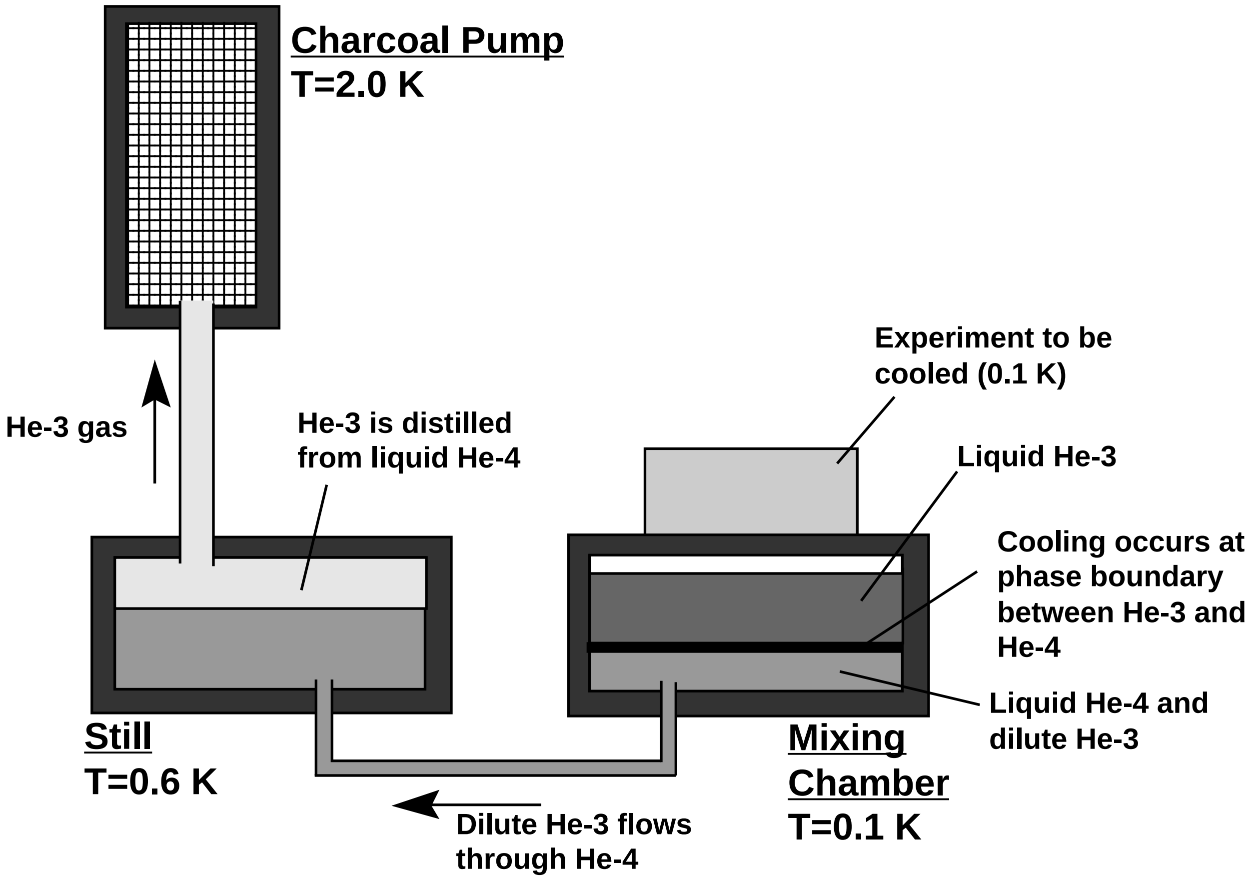

Figure 1. Operation of compact single-cycle dilution refrigerator using a charcoal pump.

flows through the He-4 to a higher temperature chamber where it is fractionally distilled from the He-4. The resulting He-3 gas is collected by the charcoal pump. The cooling cycle ends when all the He-3 is in the charcoal pump. Because the refrigerator uses adsorption onto charcoal for its pumping, all operations can be controlled by heaters and, as a consequence, there are no moving parts in the refrigerator.

Modification for Microgravity

On the ground, the operation of a dilution refrigerator depends on gravity to keep the liquid He-3 and He-4 in their correct chambers. (The charcoal pump contains no liquid and is gravity independent.) Within the dilution refrigerator there are two liquid-vapor interfaces and one liquid-liquid interface. All of these interfaces must be stably located in the absence of gravitational forces in a way that allows the free flow of the evaporated gasses and of the He-3 within the liquid phases of the refrigerator. Previous experiments[4] have shown that capillary forces in a matrix of fine pores can successfully contain liquid helium in microgravity. We have extended this approach to He-3-He-4 mixtures in a ground-based demonstration. The modifications we have made involve filling the liquid chambers of the dilution refrigerator with a sintered, porous metal matrix that confines the liquids to their correct positions by capillary forces. A critical aspect of this is the need to prevent the phase boundary between the liquid He-4 and liquid He-3 from leaving the mixing chamber. This is greatly complicated by the fact that the interfacial tension between these two phases is exceedingly small[5], only 2.0×10^{-5} N/m, compared with 1.5×10^{-4} N/m for the He-3 liquid-vapor surface tension and 3.5×10^{-4} N/m for the He-4 liquid-vapor surface tension. However, if the pores outside the region of the He-3 are small enough, and if the osmotic pressure trying to push the He-3 into these pores is not too large, the liquid He-3 will be prevented from entering the small pores containing the He-4 by the interfacial tension; the He-3 will stay in the mixing chamber where it is needed.

An obvious demonstration of the gravity independence of the dilution refrigerator would require a system many centimeters in diameter to operate properly in all orientations; this, however, is unrealistic. To use capillary forces to control the position of the various liquid-liquid and liquid-vapor boundaries under an adverse gravitational head of many centimeters of liquid on the ground, it is necessary to use very fine pores (~5 μm diam.) to contain the liquid. However, we have found that such small pores seriously impede the flow of dilute He-3 from the mixing chamber to the still; this limits the cooling power achieved and prevents the attainment of the temperature goal desired. This need not be a problem for a space-based system since the dilution refrigerator can actually use quite large pores to overcome the very small accelerations likely to be encountered in orbit. The problem is that it is necessary to test the concept of capillary confinement in a dilution refrigerator on the ground (to at least a limited extent) before committing to a flight test to provide final confirmation of the approach.

Shallow Version. We have built a shallow version of the dilution refrigerator that has a mixing chamber and still that are only 0.5 cm high; this allows us to use sinter with rather large pores (40 μm to 200 μm diam. in different locations, see Fig. 2), which we expect will permit excellent operation of the system. This design can verify a limited amount of gravity independence of the operation on the ground. In its normal position with the shallow still next to the shallow mixing chamber, and the pumping line coming out of the top of the still, it will operate even without sinter in the chambers. It would not continue to operate with the system tilted slightly so that one chamber was above the other. With the coarse sinter in the chambers, however, we expect to be able to tilt the system 5-10 degrees in either direction with little change in operation (see fig. 3). If the system is tilted more than this, either one or the other of the sinters where the connecting line attaches becomes empty, stopping the dilute He-3 circulation, or else the He-3 in the mixing chamber escapes into the surrounding small pores, allowing it to leave the mixing chamber.

In a more convincing demonstration of gravity independence, the chambers can be inverted so that the still pump line is on the bottom (see fig. 4) and the system should still operate normally. Clearly, no operation in this orientation would be possible without the sinter; the liquid in the still would simply run into the pumping line. Even in this orientation the system can be tilted 5-10

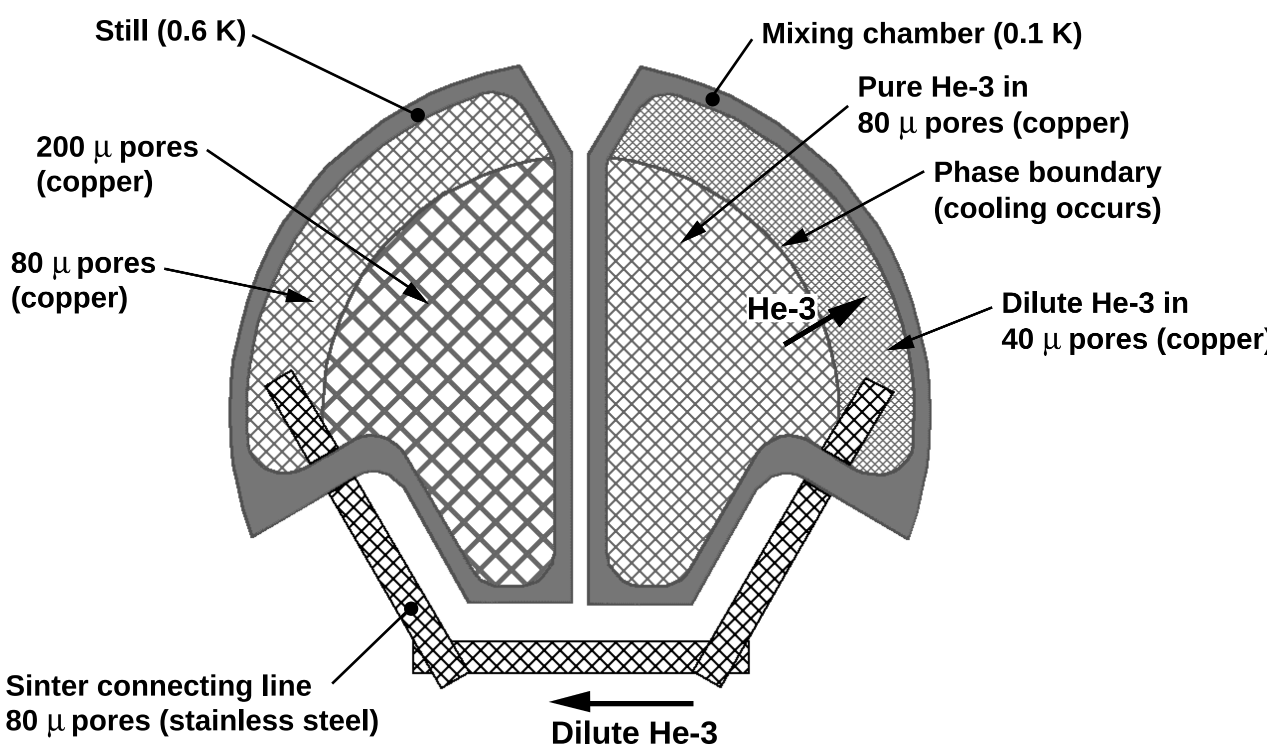

Figure 2. Arrangement of different size sinters for confining liquid helium in still and mixing chamber.

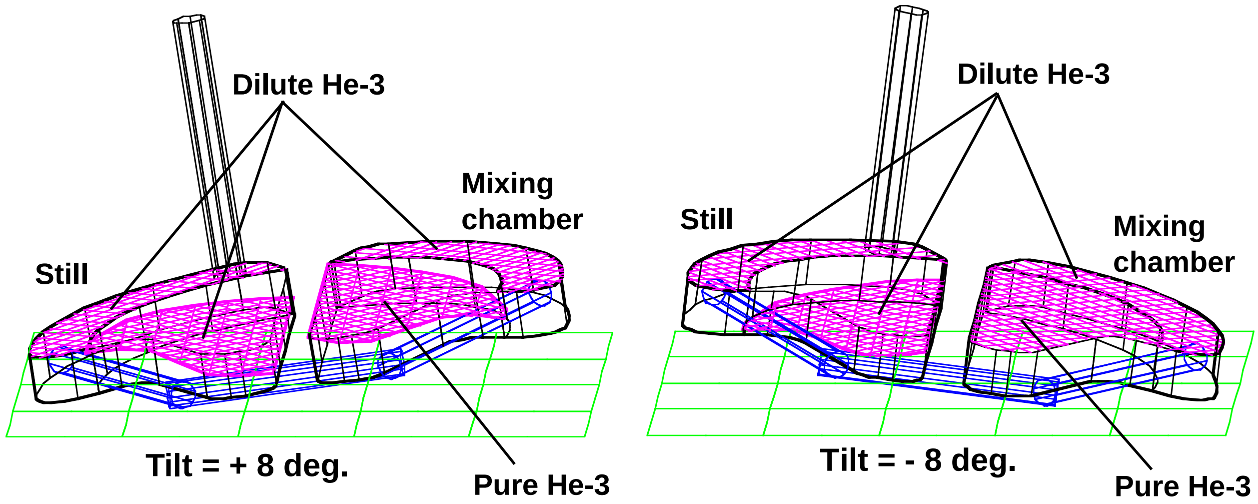

Figure 3. Distribution of liquid He as the shallow dilution refrigerator is tilted (on the ground).

degrees in either direction before the capillary forces are overcome by gravitational forces and the liquid runs from one chamber into the other. These limited confirmations of capillary confinement will be a good indication that the system will work well in space.

CONTINUOUSLY-OPERATING DILUTION REFRIGERATOR

We are developing a continuously-operating dilution refrigerator that will directly cool to 0.040 K in a microgravity environment. Such a refrigerator could also precool an adiabatic demagnetization stage for reaching temperatures of 0.001 K and below. Figure 5 shows the configuration we propose to test on the ground. The still and mixing chamber of this design are similar to those of the single-cycle refrigerator we have built. The dilute He-3 flows out of the mixing chamber into the still as before. But the He-3 gas, instead of being pumped from the still into a charcoal pump, now goes to a new chamber, the condenser, at 0.4 K, where it condenses back to a liquid and pure He-3 returns to the mixing chamber. Thus this He-3 never leaves the low-temperature region. As long as the still is heated to maintain its temperature at 0.6 K and the

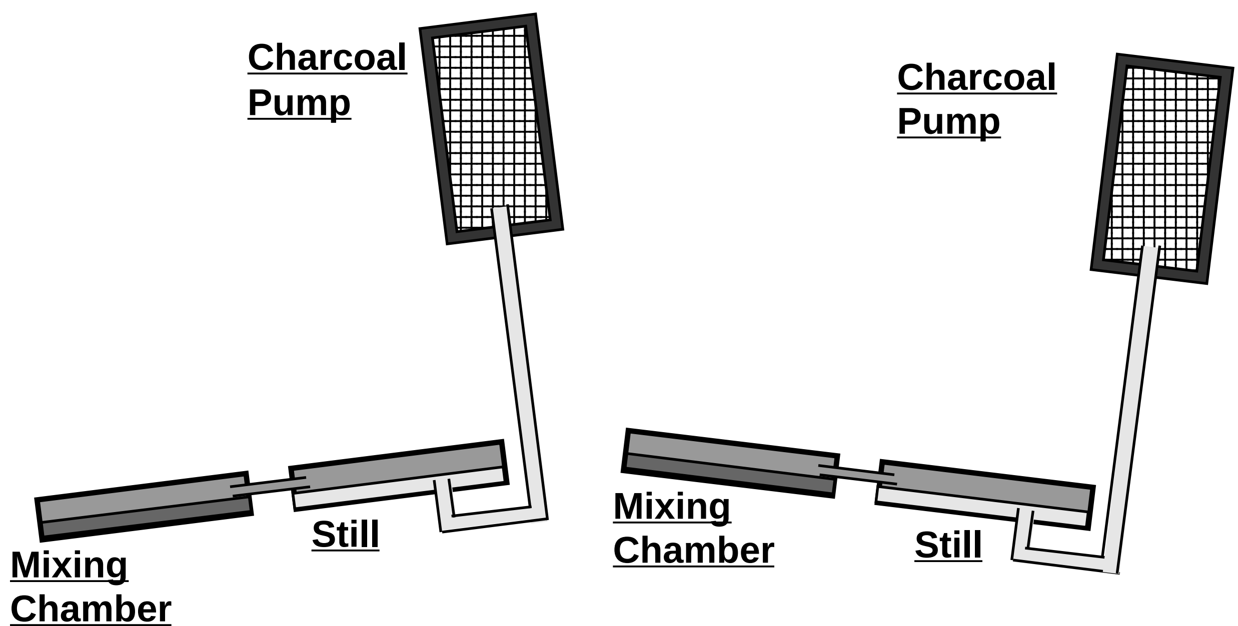

Figure 4. Shallow dilution refrigerator can be tilted even while its chambers are inverted to convincingly demonstrate gravity independence.

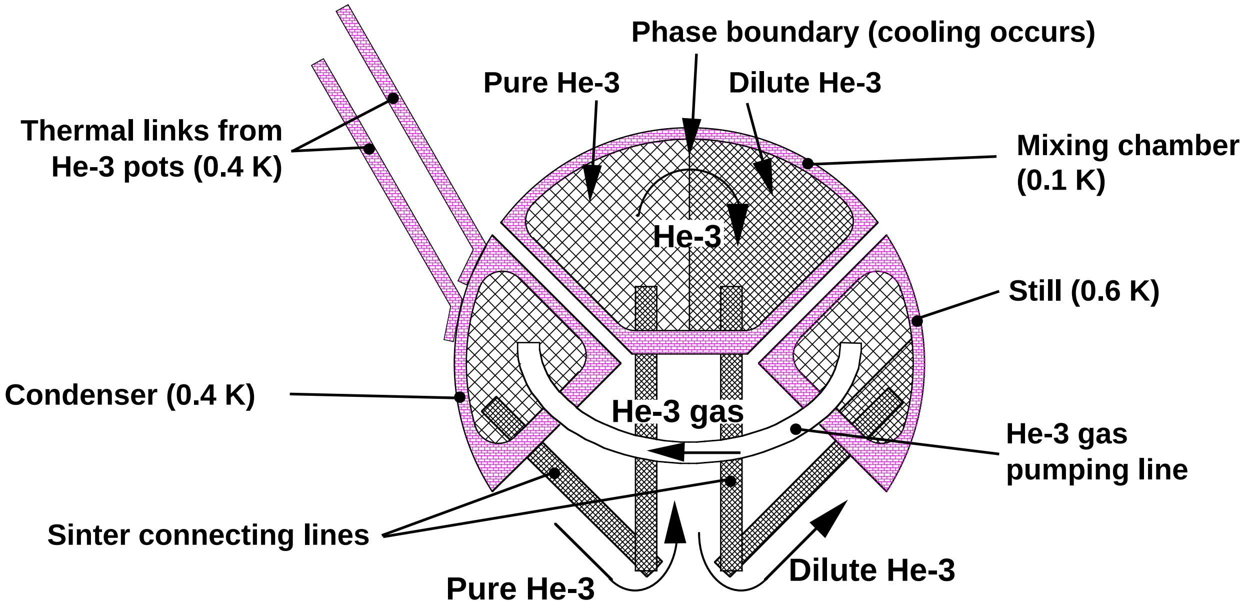

Figure 5. Details of the low-temperature chambers of the continuously-operating dilution refrigerator.

condenser is cooled to maintain its temperature at 0.4 K, He-3 will be continuously pumped from the still into the condenser and forced back into the mixing chamber. This continuous circulation of He-3 will produce continuous cooling in the mixing chamber where He-3 crosses the phase boundary from pure He-3 into the He-4.

The notable feature of this design is the method by which the condenser is continuously cooled (while maintaining the advantages of compactness, reliability and the complete absence of moving parts). The condenser is cooled by a pair of independent, single-cycle He-3 refrigerators (see Fig. 6), each with its own charcoal pump, and each thermally linked to the condenser by a gas-gap heat switch. While one He-3 pot is cold and coupled to the condenser, the other He-3 pot is isolated from the condenser while it is being refilled at high temperature. Then, before the first He-3 pot runs empty, the second He-3 pot would be cooled down and coupled to the condenser by its heat switch. The first He-3 pot could then be decoupled and refilled and there would have been no interruption of cooling to the condenser.

CONCLUSIONS

We have built a 'shallow' single-cycle dilution refrigerator to demonstrate the principle of capillary confinement in a refrigerator that can reach 0.1 K or below in microgravity. We have designed a continuously-cooling version of a dilution refrigerator that builds on the design of the single-cycle refrigerator while maintaining its advantage of no moving parts. The continuously-cooling version will be very useful by itself for microgravity experiments that require cooling to as low as 0.04 K; it will also be invaluable for experiments that require temperatures as low as 0.001 K because it can be used to precool adiabatic demagnetization systems that can reach those temperatures.

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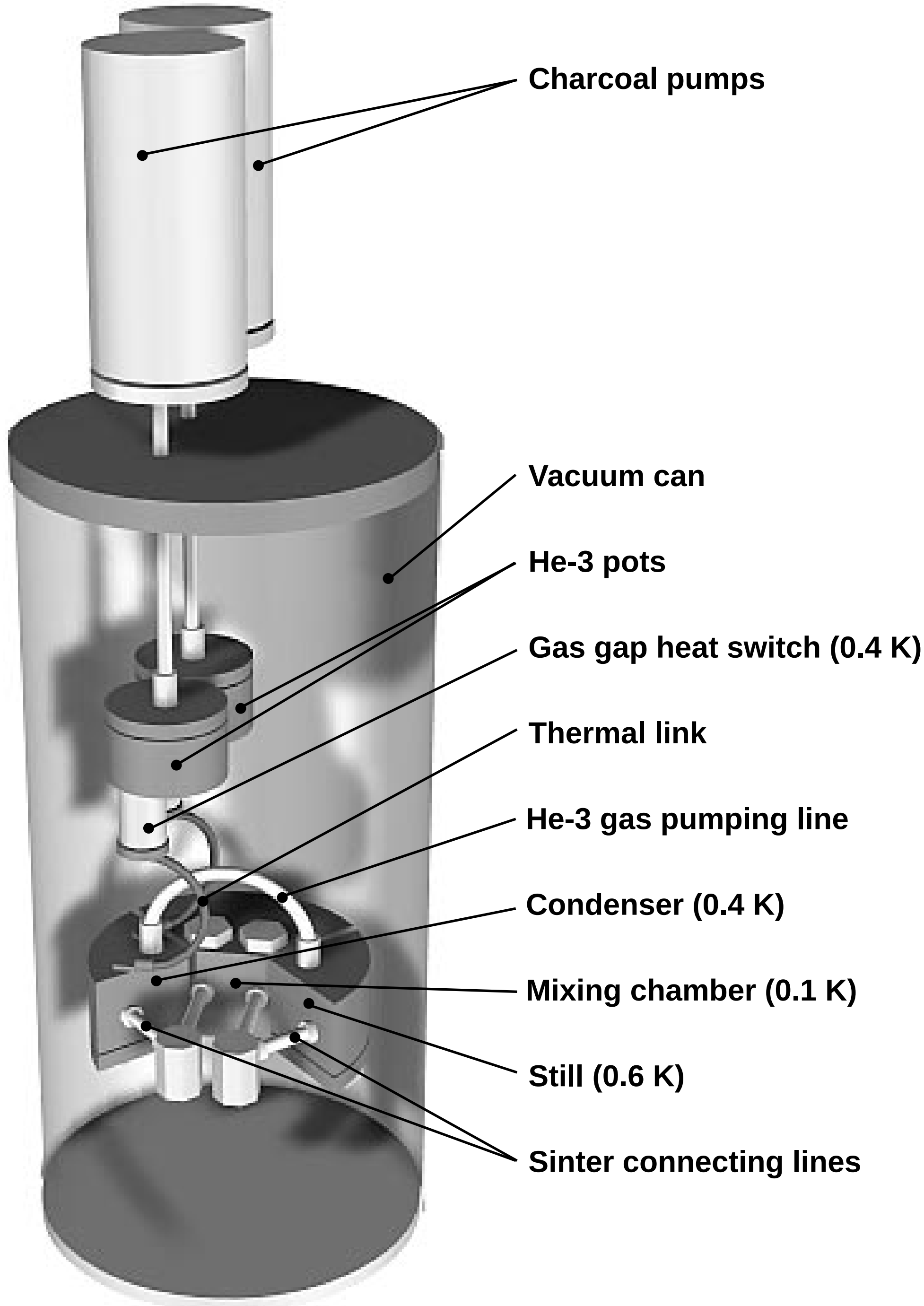

Figure 6. Components of a continuously-operating dilution refrigerator for microgravity use.

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